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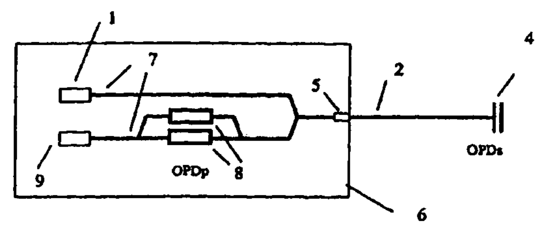
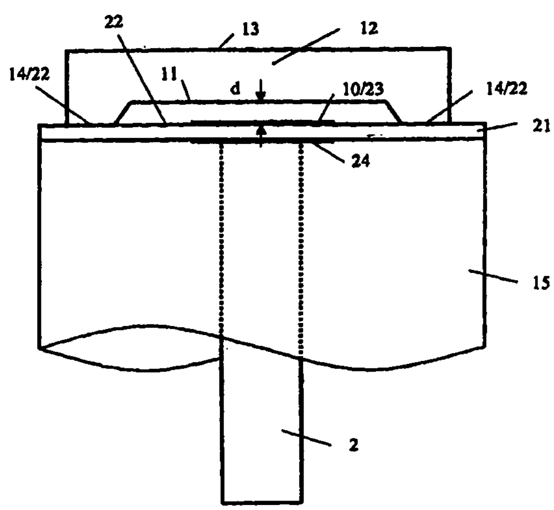
(54) Title: AN OPTICALLY ADDRESSED SENSING SYSTEM

(57) Abstract

An optically addressed sensor system is described, which uses a Fabry-Pérot interferometer (4) to sense a measurand, by way of a cavity formed by (inter alia) a micromachined diaphragm (12), setting an optical path difference OPD_S greater than the coherence length l_C of a broadband optical source (1). The output is recovered by way of a further interferometer wiht a similar optical path difference OPD_P. Thus, information is encoded in the wavelength domain, avoiding errors due to attenuation, loss, source variation etc. Suitable substrate arrangements are disclosed for the cavity which are suitable for mass production.





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AN OPTICALLY ADDRESSED SENSING SYSTEM

FIELD OF INVENTION

This invention relates to an optically addressed sensing system for sensing a parameter such as pressure or temperature, e.g. in an internal combustion engine.

BACKGROUND OF INVENTION

Optical sensors have been proposed for sensing a wide range of parameters. A variety of different sensing heads have been proposed together with a variety of different processing systems for processing the signals received therefrom. However, known arrangements tend to suffer from a variety of disadvantages and/or are not suitable for volume production.

DISCLOSURE OF THE INVENTION

The present invention aims to provide an improved sensing system which overcomes many of the disadvantages of the prior art.

It therefore provides, in its first aspect, a sensing system comprising at least one broadband light source having a coherence length l_c,

a sensing interferometer comprising first and second optical paths with an optical path difference OPD_s between them, the second optical path being subject to variation in dependence upon a parameter in the vicinity of the sensing interferometer;

the sensing interferometer being optically connected to the light source and to a processing interferometer comprising third and fourth optical paths with an optical path difference OPD_p between them;

characterised by:

the sensing interferometer comprising a diaphragm formed from a first substrate fabricated to define OPD_s,

the processing interferometer being integrated on a second substrate fabricated to define OPD_p,

both OPD_s and OPD_p being larger than l_c and the modulus of the difference between OPD_s and OPD_p being smaller than l_c.

A recess can be etched or micro-machined in at least one side of the diaphragm, the optical path difference OPD_s then being determined substantially by the depth of the recess.

The sensing interferometer is preferably connected to the light source and/or the processing interferometer by means of an optical fibre. The optical fibre at the sensing interferometer is then preferably mounted within a tube or ferrule, and the diaphragm mounted to an end face of the tube or a transparent plate mounted thereon.

A transparent plate can be provided on the end face of the tube or substrate, to define the optical cavity between the diaphragm and a surface of the transparent plate.

The sensor can suitably be used to sense pressure within an internal combustion engine.

In a second independent aspect, the present invention provides a sensor comprising: a broadband light source having a coherence length lc; a sensing interferometer having first and second optical paths along which light

from the light source is transmitted, having an optical path difference OPD_s which is less than lc, one optical path being subject to variation in dependence upon a parameter to be sensed such that information relating to the parameter is encoded in an interference signal formed by interaction of light travelling along the first and second optical paths; a processing interferometer connected to receive the interference signal from the sensing interferometer and having third and fourth optical paths of different lengths, with an optical path difference OPD_p, the sensing and processing interferometers being fabricated such that OPD_s and OPD_p are each defined with a similar degree of accuracy and so can be accurately matched to each other whereby the processing interferometer is able to decode information relating to the sensed parameter from the said interference signal.

According to a third aspect of the invention, there is provided a method of manufacturing an optical cavity for use as the sensing interferometer in an optical sensing system as detailed above, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; securing an end of an optical fibre within a bore in a tube, ferrule or further substrate; optically polishing an end face of the optical fibre and of the tube and bonding the diaphragm to the said end face of the tube by anodic bonding or diffusion bonding so an optical cavity is formed between the diaphragm and the said end face of the optical fibre, and the length of the optical cavity is substantially determined by the depth of the recess.

According to a fourth aspect of the invention, there is provided a method of manufacturing an optical cavity for use as the sensing interferometer in a sensing system as detailed above, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; bonding the diaphragm to one face of a transparent plate by anodic or diffusion bonding so as to define an optical cavity therebetween the length of which is substantially determined by the depth of the recess; bonding the opposite surface of the transparent plate to an end face of a tube, ferrule or further

substrate; and securing an end of an optical fibre within the tube or ferrule or further substrate.

According to a further aspect of the invention, there is provided a sensor comprising a glass substrate including a bore therein for receiving an optical fibre, and a further substrate which is etched to form a recessed region surrounded by a raised support, the support being bonded in place such that the recessed region is over the bore axis, characterised in that the etching of the further substrate is deeper than 10μm.

Other preferred and optional features of the invention will be apparent from the following description and from the subsidiary claims of the specification.

BRIEF DESCRIPTION OF DRAWINGS

The invention will now be further described, merely by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of a sensor according to one embodiment of the invention;

Figure 2 is a schematic diagram of a sensor cavity used in the sensor of Figure 1;

Figure 3 is a schematic diagram of another embodiment of a sensor according to the invention;

Figures 4a and 4b show cross-sectional views of a sensor diaphragm used in the sensor head of Figure 2;

Figure 5 illustrates a method of fixing an optical fibre in a capillary in the fabrication of a sensor head such as that shown in Figure 2;

Figure 6 illustrates one way of mounting a diaphragm such as shown in Figure 4a or 4b in a sensor head such as that shown in Figure 2;

Figure 7 illustrates another method of fixing an optical fibre in a capillary in the fabrication of a sensor head such as that shown in Figure 2;

Figure 8 illustrates another way of mounting the diaphragm in the sensor head;

Figure 9 illustrates a still further way of mounting the diaphragm in the sensor head; and

Figure 10 illustrates a sensor according to a further embodiment of the invention.

DETAILED DESCRIPTION OF THE EMBODIMENT

Figure 1 illustrates schematically a white-light measurement system based on a integrated interferometer, ie an interferometer formed of appropriate structures on a single substrate. Light from a broad-band light source 1 is fed into an optical fibre 2 and routed via an optical fibre Y-junction 3 to a pressure sensor head 4. An interference signal returning from the sensor head 4 is analysed by a processing interferometer integrated onto a substrate 6 and an output representing the sensed pressure provided by a light detector 9. In an actual embodiment, the light source and the light detector could be interchanged. However, for simplicity, the remainder of this description will assume that these are arranged as shown in figure 1.

A white-light sensor system is one that employs a broad-band light source, emitting light within a range of wavelengths determined by its spectral width $\Delta\lambda$. The coherence length l_c of the source is closely related to the spectral width, and is given by the approximate relationship $l_c \sim \lambda_{peak}^2/\Delta\lambda$, with λ_{peak} being the centre wavelength of the emission spectrum. Typically, $\Delta\lambda$ ranges from 30nm to 50nm for superluminescent diodes (SLD) emitting around 1.3μm, resulting in a short coherence length between 55μm and 35μm, respectively.

A schematic of the sensor head is shown in Fig 2. It comprises an optical cavity which essentially consists of two reflective interfaces 10 and 11 connected to the optical fibre 2. The distance d between these two interfaces changes if external pressure p is applied. In its simplest form, interface 10 is created by the fibre-air interface and interface 11 is formed by a diaphragm which deflects in response to the applied pressure. A portion of the light sent to the sensor head is backreflected at the first interface 10. The remaining light is reflected at the second interface 11 and subsequently recaptured by the fibre 2. Hence, an optical path difference $OPD_S = 2d$ is created between these two beams returned from the sensor head. The change in distance Δd induced by the applied pressure generates an additional phase shift $\Delta\phi=2\pi\Delta d/\lambda_{peak}$ on top of the already existing phase difference $\phi_0=2\pi 2d/\lambda_{peak}$ between the two beams. However, they will not interfere with each other on recombination at the fibre tip as OPD_s is deliberately designed to be substantially larger than the coherence length l_c of the light source. To fulfill this condition it is sufficient in practice that OPD_S is about three times larger than the coherence length, leading to a minimum OPD_S between 90μm and 150μm. As a result of this design, the additional phase shift $\Delta\phi$ between both beams generated by the applied pressure cannot be recovered using only this single interferometer (the sensing interferometer).

In order to appreciate the advantages of white-light interferometry, it is useful to consider the wavelength domain. After passing through the sensing interferometer with an $OPD_s >> l_c$, the light from the broad band source contains a number of maxima and minima relating to constructive or destructive interference at the corresponding wavelength. This is referred to as a channelled spectrum. A change in OPD_s will cause a change in the interference conditions, resulting in a shift in wavelength of the whole channelled spectrum. Hence, the signal information is encoded in the wavelength domain and any intensity fluctuations in the system do not affect the measurement results.

By feeding the output of the sensing interferometer into a second interferometer (the processing interferometer) with an OPD_p substantially equal to the OPD_s of the sensing interferometer ($|OPD_p - OPD_s| << l_c$), a portion of the two beams can be brought back in phase again. If the processing interferometer is of substantially the same OPD as the sensing interferometer, a maximum transmission is generated. Due to the limited coherence length of the light source employed, any deviation from the condition $OPD_s = OPD_p$ will result in a decrease in visibility until it drops to zero for $|OPD_p - OPD_s| >> l_c$. The result is a sinusoidal fringe pattern under a Gaussian-type envelope with the maximum value (central fringe) occurring at $OPD_s = OPD_p$.

In order to maintain a sufficiently high visibility of the signal output, the difference $OPD_p - OPD_s$ should be smaller than typically around 5 μm.

The matching of the two OPD's is critical for useful operation of the sensor. As the assembly of the processing interferometer and the sensor head are two independent processes, it is important to be able to control the OPD of both elements separately to a high degree of accuracy.

The control of OPD_p can be achieved by employing (for example) a Mach—Zehnder interferometer realised in integrated form on an optical chip 6

as shown in Fig 1. The integrated Mach-Zehnder interferometer comprises integrated waveguides 7, including Y-junctions, integrated phase modulators 8, and means 5 for coupling optical fibres to the integrated waveguides 7.

Further details of a suitable integrated interferometer are given in the applicants' co-pending applications GB9623762.3 (Publication no. GB 2319335A) and PCT/GB97/03144 (Publication no. WO98/22775) and the other applications mentioned therein WO95/08787 and WO97/42534.

By employing an integrated version it is ensured that the OPD_p of the Mach-Zehnder interferometer can be determined to a very high accuracy. Typically, a variation in OPD_p of less than 2 to 3 µm is routinely achievable. This accuracy can be maintained in a production process and is highly repeatable.

In a preferred embodiment of the sensor, the light source 1 and detector 9 are also integrated on the same chip. The schematic layout of such an arrangement is shown in Figure 3.

The manufacture of a sensor head 4 with an accurately determined OPD_s which is repeatable in a production process also requires particular attention. For instance, in-fibre Fabry-Perot cavities for pressure sensing have been demonstrated using a section of fibre both ends of which have been coated with a TiO_2 layer to form low reflective mirrors. This section is than spliced onto a lead fibre. In this configuration it is difficult to determine and repeatedly produce an OPD of fixed value to an accuracy of a few microns. Similarly, metal diaphragms could be used in a pressure sensor head cavity but they do not allow for maintenance of a highly accurate cavity length in a manufacturing environment. The fabrication of sensor heads with an accurately determined and reproducible OPD_s is thus a critical component of the present invention.

An important aim of the present invention is to describe optical pressure sensor heads which can be made repeatedly and accurately to a specified OPD_S so that they can be used in the white-light measurement system employing an integrated processing interferometer, as explained above. The invention uses well established silicon micromachining techniques to produce diaphragms of specified geometrical dimension and pressure sensitivity. This is combined with ways of fixing the diaphragms in front of an optical fibre in order to form a sensing cavity of the required OPD_S. Silicon is widely used in mechanical engineering applications due to its excellent mechanical properties. It offers a high degree of dimensional control during processing and can be manufactured on a wafer scale, enabeling cost effective batch fabrication.

The starting point for the manufacture of the diaphragm is a silicon wafer of appropriate thickness t_w which is polished at least on one side. A number of chemicals (wet etchants) with varying degree of selectivity to silicon and isotropic or anisotropic etching behaviour are copmonly used. For instance, using an anisotropic etchant such as potassium hydroxide, the (100) surface is etched at a rate about 400 times faster than the (111) surface. This leads to the forming of structures with a characteristic angle of 54.74° for a (100) orientated wafer. Appropriate masking techniques use materials such as silicon oxide or silicon nitride in conjunction with different etchants to provide great design flexibility. Fig 4 is a side view of a diaphragm 12 which is formed by one-sided etching of a silicon wafer from its polished side 14.

One key point for the white-light application is that the silicon etch rates are accurately determined by the processing conditions for a given etchant. As a result, the etch depth d is easily controlled to an accuracy of better than about 1 to 2µm under manufacturing conditions. The anisotropic wet etching process provides a flat surface 11 of high surface quality which can be used without any further preparation as one of the interfaces forming the Fabry-Perot sensing cavity. Its reflectivity is determined by the value of the refractive index step between air and silicon. Given a refractive index n_{Si} of 3.5 for silicon at a

wavelength of 1310nm and $n_{air} = 1$, the reflectivity $R = (n_{Si} - 1)^2/(n_{Si} + 1)^2$ of the surface 11 equals about 30%. The second interface 10 required to form the sensing cavity can be provided in a number of different ways. In the particular examples considered in more detail below, the second reflective interface is flush with the surface 14. Hence, the OPD of the sensing cavity equals $2dn_{air} = 2d$ and together with the ability to accurately control the etch depth d, this enables the manufacture of sensor heads with an accurately predetermined OPD_S.

The portion of light which is not reflected from the first air-silicon interface 11 will propagate through the diaphragm of thickness t and is partly reflected back at the outer silicon-air interface 13, parallel to interface 11. Hence, a second cavity with an OPD equal to $2n_{Si}t$ is created. This does not have any adverse effects on the system performance, so long as $2n_{Si}t$ is sufficiently different from the OPD of the sensing cavity OPD_S. However, if the design of the diaphragm requires a diaphragm thickness t so that $2n_{Si}t$ roughly equals OPD_S, additional measures should be taken to avoid possible signal corruption. Such a design may be required in order to achieve a specific sensitivity within geometrical restrictions, as the diaphragm sensitivity is mainly determined by the diaphragm thickness t and geometrical factors such as its diameter and shape. The adverse effects of the second cavity can be avoided by depositing a thin layer of metal onto the reflecting surface 11 in order to enhance its reflectivity, hence minimising the amount of light in the second cavity.

Several considerations for the choice of metal should be taken into account. The metal should provide a sufficiently high reflection coefficient in the considered wavelength region, it should adhere reliably to silicon and its surface should not degrade over time or in harsh operating conditions such as elevated temperatures. One suitable choice is chromium, which will enhance the reflectivity of the surface 11 to about 60% in the 1310nm wavelength region. This enables the efficient suppression of adverse effects on the system performance generated by the second cavity. The minimum metal thickness is

determined by the 'skin' effect of the metal. As long as the deposition thickness exceeds the skin depth, a constant reflection coefficient with increasing thickness is observed. In the case of chromium, a deposition thickness of about 300nm is sufficient. Making the metal layer excessively thick changes the mechanical properties of the diaphragm and enhances the likelihood of adhesion failure.

An additional benefit of depositing a metal layer onto surface 11 is to benefit the overall resolution of the system. Often, the resolution of an optical measurement system based on white-light interferometry is limited by noise generated due to the low level of light power received at the detector. One way of achieving a higher system resolution is to enhance the amount of light returned from the sensor cavity. A metal coating on the inside of the diaphragm will therefore enhance the reflectivity of the surface 11, and hence lead to a higher signal-to-noise ratio.

It will be appreciated that the above discussion is not restricted to the particular diaphragm design shown in Fig 4a and is also valid for other micromachined designs. In particular, it is possible to etch the silicon wafer from both sides, and hence change the sensitivity by reducing the effective diaphragm thickness t for a given diaphragm diameter and fixed etch depth d. A schematic of a double-etched diaphragm is shown in Fig.4b. As a result, this additional design parameter allows changes to be made to the diaphragm sensitivity without requiring changes in the OPD_S of the sensing cavity.

The optical pressure sensor described in the present invention is based on a Fabry-Perot type cavity as shown schematically in Fig.2. The following discussion deals with a number of ways of providing the second surface 10 of the sensing cavity. These options ensure the accurate positioning of this surface 10, and together with the high accuracy of the etch depth d, this will provide an accurately predetermined OPD_S of the pressure sensor cavity required for proper operation of the white-light system.

Example 1

In this case the end face of the optical fibre 2 leading to the sensor head acts as the second reflecting interface 10 of the sensing cavity. The flat air-glass interface is provided by polishing to an optical grade finish, yielding a reflectivity of about 3.5% according to $R = (n_{Glass} - 1)^2/(n_{Glass} + 1)^2$ with n_{Glass} = 1.45 being the refractive index of the optical fibre. In order to polish the fibre and to fix it in front of the diaphragm, an auxiliary support element is required. This is provided by a glass micro-capillary 15 with an inner diameter of about 126 to 128μm to fit a standard single mode fibre with a nominal diameter of 125μm (see Fig 5). The fibre is fixed in the micro-capillary by an appropriate low-viscosity adhesive to provide sufficient bonding between fibre and capillary. It is preferred to use micro-capillaries which have a conical opening 16 at the rear end from which the fibre and adhesive can be easily inserted. In addition, the opening can be filled with adhesive 17 to provide protection for the fibre. Polishing the assembled fibre-capillary assembly will ensure that the polished fibre end 10 is flush with the polished end face 18 of the capillary. The bonding line 19 between fibre and micro-capillary is deliberately kept thin to ensure that damage to the fibre end during polishing is minimised. If the bond line were considerably thicker the polishing procedure would lead to a build-up of stress in the fibre and capillary, resulting in the formation of cracks within the optical fibre. This would damage the light guiding properties of the fibre and render the sensor cavity useless.

By mounting the silicon diaphragm directly onto the micro-capillary as shown in Fig 6, the distance between the two reflective mirrors 10 and 11 of the sensing cavity (and hence OPD_S) is accurately determined by the etch depth d of the silicon diaphragm. Two possible ways of mounting techniques are explained in more detail below.

Usually, the fibre mounted in the micro-capillary experiences some degree of temperature induced movement relative to the capillary, mainly due

to a possible mismatch in the thermal expansion coefficients between fibre and capillary. In dependence on the temperature changes experienced, typical movements range from nanometers to about one μm. This is not a problem as long as the thermally induced drift is slow in comparison to the timescale of the pressure changes. However, for static or quasi-static pressure measurements any thermally induced drift in the fibre position is interpreted by the system as a pressure change and hence creates a measurement error in the form of a finite temperature-cross sensitivity. It can also be a problem if a dynamic pressure probe is required to operate over a very large temperature range as the associated drift may exceed the tracking range of the processing interferometer. In order to minimise this drift effect, the fibre is rigidly fixed at the front end of the capillary. This can be achieved by locally heating the capillary, employing (for instance) a laser or a localised heating element, and allowing the capillary to collapse along a limited section 20 of up to a few mm's. The micro-capillary is then back-polished until the collapsed region is reached as shown in Fig 7. In this way, any movements induced due to thermal mismatch between fibre and capillary will occur at the back end of the capillary, i.e. near the cone, leaving the position of the reflective surface 10 flush with the front capillary face 18. The adhesive 17 applied to the cone should be somewhat flexible after curing to give way to the small movements involved and at the same time, still protecting the fibre. In this way, the build-up of significant stress levels in the fibre is avoided.

Until now the only requirement regarding the type of glass used for the micro-capillary was that it would be suitable for polishing. However, if the micro-capillary is made of PYREX or borosilicate glass, one can take advantage of a process known as anodic bonding in order to fix the silicon diaphragm onto the glass micro-capillary, i.e. bonding surface 14 onto surface 18. Anodic bonding is widely used in the field of silicon micromachining and provides a strong, reliable and hermetic bond. It is a combined thermal and electrostatic process, carried out at elevated temperature with the assistance of an electrostatic field. Both the silicon and the glass surface to be joined must

be sufficiently clean and flat. The required surface finish is automatically guaranteed in this assembly procedure due to previous process steps. Silicon wafers with one or two sides polished are commercially available and the polishing of the micro-capillary front face 18 was carried out in order to obtain a flat fibre end. Hence, apart from the cleaning of the two surfaces, no additional steps are required for preparation of the anodic bonding process.

Example 2

In this case, an additional thin, flat transparent cover plate 21 is employed to provide the second reflective interface 10 of the sensing cavity. It is formed by the upper plate interface as shown in Fig 8. This assembly is later fixed onto the micro-capillary 15 holding the optical fibre 2 in place. Two major advantages result from this configuration. First, the OPD_S of the sensing cavity is accurately determined by the etch depth of the diaphragm d only. Possible drifts of the fibre within the micro-capillary will not change OPD_S. Secondly, the diaphragm-plate assembly can be manufactured on a wafer level. For instance, the thin plate can be formed by a thin borosilicate glass wafer with polished surfaces, which is commercially available. Such a wafer can be anodically bonded onto the silicon wafer into which the diaphragms have been etched.

The addition of the transparent plate creates an additional cavity similar to the cavity formed by the silicon diaphragm itself as discussed above. In order to minimise possible adverse effects, a reflective coating 23 can be applied to the upper surface 22 of the plate 21 in addition to the optional metal coating on the inside of the diaphragm 11. Also, it is possible to apply an anti-reflection (AR) coating 24 onto the lower side of the plate 21. The application of these coatings are favourably carried out on a wafer-scale level.

After dicing the diaphragm-plate assemblies, they can be fixed onto empty micro-capillaries. The optical fibre is inserted into the capillary afterwards and can be fixed by appropriate adhesive. To ensure proper optical

performance, the fibre only has to be cleaved as the fibre end face is no longer part of the cavity. This removes the labour intensive step of polishing capillaries containing a fibre lead at the rear end or the capillary.

A different realisation of the second option employs a silicon wafer instead of a glass wafer to form the additional plate 21. Bonding the silicon wafers containing the diaphragms to the wafer 21 is achieved by silicon fusion bonding, known to provide a strong, reliable bond. Typically, silicon diffusion bonding requires a much higher processing temperature in comparison to anodic bonding at around 300°C. However, as the diaphragm-plate assembly is fabricated without an optical fibre present, this is not a disadvantage. The advantage of employing a silicon plate is that the diaphragm-plate assembly can be fixed onto a borosilicate micro-capillary by anodic bonding, avoiding the use of adhesives at this stage. As the anodic bonding process relies on a good electrical contact at the glass-silicon interface, the optional AR-coating 24 should be recessed in this case by a small amount. The reason is that AR-coatings are typically formed by a combination of dielectric layers which are electrically isolating. The recess 25 is easily formed by etching the silicon wafer 21 at the appropriate locations (see Fig 9) prior to depositing the AR-coating and carrying out the anodic bonding to the capillary 15.

In the proceeding discussions the use of a borosilicate micro-capillary is described. Alternatively, a quartz micro-capillary could be employed. Quartz glass is easy to polish, and fixtures between the quartz capillary and the silicon wafer can be provided by a process known as diffusion bonding. Similar to anodic bonding, diffusion bonding provides a strong, reliable bond but requires an additional thin layer of metal (for instance, Gold) deposited onto one (or both) corresponding surfaces to facilitate bonding.

Finally, a different way for mounting the fibre in front of the silicon diaphragm makes use of solder glass. Solder glasses are widely used in the electronics industry for sealing purposes, providing robust adhesion and high

reliability. This approach replaces the need for fixing the optical fibre in a micro-capillary. Instead of employing a separate glass capillary, a glass tube around the fibre is formed using solder glass. Glass solder softens on heating and at a sufficiently high temperature starts to flow and behave similarly to a liquid. Hence, the solder glass can be made to flow into a cylindrical shape. A large variety of glass powders with different properties are available, or can be designed ad hoc. The difference in thermal expansion coefficients between fibre and solder glass can be minimised through appropriate selection. In this way, the fibre is fixed rigidly in the glass mould. This assembly is polished afterwards to provide the second surface 10 of the sensing cavity. Anodic bonding of the silicon diaphragm to the polished assembly can be carried out if an appropriate type of solder glass is employed.

Solder glass can also be employed to replace adhesive used for fixing the optical fibre in a separately provided micro-capillary as described earlier.

It will be appreciated that the sensor described above relies on the accurate fabrication of both the integrated processing interferometer and the sensing interferometer so that OPD_p and OPD_s are accurately matched. The use of etched or micro-machined silicon in the fabrication of a Fabry-Perot sensor cavity has previously been proposed, but only in conjunction with arrangements which suffer from significant disadvantages such as limited dynamic range, sensitivity to losses in the optical fibre leading to the sensor head and to the light source and/or detector and relatively small signal bandwidth. These problems are overcome by combining the use of an integrated processing interferometer with the accurate fabrication of a sensor head which enable the use of a white-light processing technique as described above. Furthermore, it will be appreciated that the sensor described above is suitable for volume manufacture.

It will be appreciated that the invention is not restricted to the measurement of pressure. In more general terms, any environmental change

which changes OPD_S can be measured, leading to the detailed advantages of the described system for other measurands.

For instance, temperature sensing can be accomplished, for example, with a sensing cavity formed by a plate 12 of silicon bonded to the glass capillary 15 in which the optical fibre 2 is fixed. In this case, the reflective surfaces of the cavity are given by the two surfaces 11A, 13A of the plate 12. A change in ambient temperature will change the refractive index of silicon and hence, change the optical path length of the beam reflected at the outer surface 11A. Silicon etching or micromachining can be used to etch an appropriate recess in the outer surface opposite the fibre so that the remaining plate thickness t_p equals the required $OPD_S = 2n_{Si}t_p$. As before, OPD_S is accurately determined by the etch depth.

Another way to measure temperature would be with a similar sensor head arrangement as shown in Fig. 6, 8 or 9 where the plate 12 is made thick enough so that the distance d of the optical cavity expands or contracts due to expansion or contraction of the raised support of the plate12 as the temperature changes.

CLAIMS

1. A sensing system comprising at least one broadband light source having a coherence length l_c,

a sensing interferometer comprising first and second optical paths with an optical path difference OPD_s between them, the second optical path being subject to variation in dependence upon a parameter in the vicinity of the sensing interferometer;

the sensing interferometer being optically connected to the light source and to a processing interferometer comprising third and fourth optical paths with an optical path difference OPD_p between them;

characterised by:

the sensing interferometer comprising a diaphragm formed from a first substrate fabricated to define OPD_s,

the processing interferometer being integrated on a second substrate fabricated to define OPD_p,

both OPD_s and OPD_p being larger than l_c and the modulus of the difference between OPD_s and OPD_p being smaller than l_c.

2. A system as claimed in Claim 1 in which a recess is etched or micro-machined in at least one side of the first substrate of which the diaphragm is formed, the optical path difference OPD_s being determined substantially by the depth of the recess.

3. A system as claimed in Claim 1 or 2 in which said first substrate is silicon.

4. A system as claimed in Claim 1, 2 or 3 in which the sensing interferometer is connected to the light source and/or the processing interferometer by means of one or more optical fibres.

5. A system as claimed in Claim 4 in which the end of the optical fibre at the sensing interferometer is mounted within a bore in a substrate and the

diaphragm mounted to an end face of the said substrate or a transparent plate mounted thereon.

6. A system as claimed in any preceding Claim in which the diaphragm is etched to have a centrally recessed sensor region surrounded by a raised support, the support being bonded in place such that the centrally recessed region is over the bore axis, the diaphragm providing a reflective surface forming part of the second optical path of the said sensing interferometer.

7. A sensor comprising a glass substrate including a bore therein for receiving an optical fibre, and a further substrate which is etched to form a recessed region surrounded by a raised support, the support being bonded in place such that the recessed region is over the bore axis, characterised in that the etching of the further substrate is deeper then 10μm.

8. A system as claimed in any one of Claims 5 to 7, said substrate including the bore being a tube or ferrule.

9. A system as claimed in any one of Claims 5 to 8 in which the substrate, tube or ferrule is borosilicate glass or quartz glass.

10. A system as claimed in Claims 5 to 9 wherein the bore includes a stop against which the fibre can abut, the bore being a through bore.

11. A system as claimed in any one of Claims 5 to 10 wherein the bore is a blind bore, the end face of the bore providing a stop against which the fibre can abut.

12. A system as claimed in any one of Claim 5 to 11 in which the transparent plate is of silicon or borosilicate glass or quartz glass.

13. A system as claimed in any one of Claim 5 to 12 in which an optical cavity is defined between the said end of the optical fibre and the diaphragm or the transparent plate and the diaphragm.

14. A system as claimed in any one of Claim 5 to 13 in which the optical fibre is secured within the bore by adhesive, solder glass, mechanical crimping or collapsing by heating of the substrate surrounding the bore.

15. A system as claimed in any one of Claims 5 to 14 in which a flexible sealant is provided between the optical fibre and the substrate surrounding the bore at the free exit of the bore.

16. A system as claimed in any one of Claim 5 to 15 wherein the securing is limited to the section of the optical fibre within the substrate or tube or ferrule nearest to the end of the fibre.

17. A system as claimed in any one of Claim 5 to 16 in which the diaphragm is bonded to the end face of the tube or to the transparent plate mounted thereon by anodic bonding or diffusion bonding.

18. A system as claimed in any one of Claims 10 to 17 in which the reflectivity of one or both of the interfaces defining the cavity is increased by the provision of a reflective coating thereon.

19. A system as claimed in any preceding Claim in which the substrate comprising the processing interferometer is silicon or silicon-on-insulator or silica-on-silicon.

20. A system as claimed in any preceding Claim in which the processing interferometer is a Mach-Zehnder or Michelson interferometer.

21. A system as claimed in any preceding Claim in which the broadband light source(s) is integrated on the substrate comprising the processing interferometer.

22. A system as claimed in any preceding Claim in which a light detector is integrated on the substrate comprising the processing interferometer.

23. A system as claimed in any preceding Claim in which the broadband light source is a superluminescent diode.

24. A system as claimed in any preceding Claim in which the coherence length l_c of the broadband light source is in the range 35-55 μm.

25. A system as claimed in any preceding Claim in which OPD_s is in the range 100-160μm.

26. A system as claimed in any preceding Claim in which the difference between OPD_s and OPD_p is 5μm or less.

27. An optical sensing system substantially as hereinbefore described with reference to the accompanying drawings.

28. A sensing system as claimed in any preceding Claim arranged to sense pressure within an internal combustion engine.

29. A method of manufacturing an optical cavity for use as the sensing interferometer in an optical sensing system as claimed in any preceding Claim, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; securing an end of an optical fibre within a bore in a tube, ferrule or further substrate; optically polishing an end face of the optical fibre and of the tube and bonding the diaphragm to the said end face of the tube by anodic bonding or diffusion

bonding so an optical cavity is formed between the diaphragm and the said end face of the optical fibre, and the length of the optical cavity is substantially determined by the depth of the recess.

30. A method of manufacturing an optical cavity for use as the sensing interferometer in a sensing system as claimed in any of Claims 1 - 28, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; bonding the diaphragm to one face of a transparent plate by anodic or diffusion bonding so as to define an optical cavity therebetween the length of which is substantially determined by the depth of the recess; bonding the opposite surface of the transparent plate to an end face of a tube, ferrule or further substrate; and securing an end of an optical fibre within the tube or ferrule or further substrate.

31. A sensor comprising: a broadband light source having a coherence length lc; a sensing interferometer having first and second optical paths along which light from the light source is transmitted, having an optical path difference OPD_s which is less than lc, one optical path being subject to variation in dependence upon a parameter to be sensed such that information relating to the parameter is encoded in an interference signal formed by interaction of light travelling along the first and second optical paths; a processing interferometer connected to receive the interference signal from the sensing interferometer and having third and fourth optical paths of different lengths, with an optical path difference OPD_p, the sensing and processing interferometers being fabricated such that OPD_s and OPD_p are each defined with a similar degree of accuracy and so can be accurately matched to each other whereby the processing interferometer is able to decode information relating to the sensed parameter from the said interference signal.

32. A sensor as claimed in claim 31 in which the parameter to be measured is pressure.

33. A sensor as claimed in claim 31 in which the parameter to be measured is temperature.

AMENDED CLAIMS

[received by the International Bureau on 05 November 1999 (05.11.99); original claims 2 and 31-33 cancelled; original claim 1 amended; original claims 3-30 amended and renumbered as claims 2-29 (5 pages)]

1. A sensing system comprising at least one broadband light source having a coherence length l_c,

   a sensing interferometer comprising first and second optical paths with an optical path difference OPD_s between them, the second optical path being subject to variation in dependence upon a parameter in the vicinity of the sensing interferometer;

   the sensing interferometer being optically connected to the light source and to a processing interferometer comprising third and fourth optical paths with an optical path difference OPD_p between them;

   characterised by:

   the sensing interferometer comprising a diaphragm formed from a first substrate in which a recess is etched or micro-machined in at least one side of the first substrate so the optical path difference OPD_s is determined substantially by the depth of the recess,

   the processing interferometer being integrated on a second substrate fabricated to define OPD_p,

   both OPD_s and OPD_p being larger than l_c and the modulus of the difference between OPD_s and OPD_p being smaller than l_c.

2. A system as claimed in Claim 1 in which said first substrate is silicon.

3. A system as claimed in Claim 1 or 2 in which the sensing interferometer is connected to the light source and/or the processing interferometer by means of one or more optical fibres.

4. A system as claimed in Claim 3 in which the end of the optical fibre at the sensing interferometer is mounted within a bore in a substrate and the diaphragm mounted to an end face of the said substrate or a transparent plate mounted thereon.

5. A system as claimed in any preceding Claim in which the diaphragm is etched to have a centrally recessed sensor region surrounded by a raised support, the support being bonded in place such that the centrally recessed region is over the bore axis, the diaphragm providing a reflective surface forming part of the second optical path of the said sensing interferometer.

6. A system as claimed in any preceding claim in which the sensing interferometer includes a sensor comprising a glass substrate including a bore therein for receiving an optical fibre, and a further substrate which is etched to form a recessed region surrounded by a raised support, the support being bonded in place such that the recessed region is over the bore axis, characterised in that the etching of the further substrate is deeper then 10μm.

7. A system as claimed in claim 6, said substrate including the bore being a tube or ferrule.

8. A system as claimed claim 6 or 7 in which the substrate, tube or ferrule is borosilicate glass or quartz glass.

9. A system as claimed in claim 6, 7 or 8 wherein the bore includes a stop against which the fibre can abut, the bore being a through bore.

10. A system as claimed in any one of Claims 6 to 9 wherein the bore is a blind bore, the end face of the bore providing a stop against which the fibre can abut.

11. A system as claimed in any one of Claim 6 to 10 in which the transparent plate is of silicon or borosilicate glass or quartz glass.

12. A system as claimed in any one of Claim 6 to 11 in which an optical cavity is defined between the said end of the optical fibre and the diaphragm or the transparent plate and the diaphragm.

13. A system as claimed in any one of Claim 6 to 12 in which the optical fibre is secured within the bore by adhesive, solder glass, mechanical crimping or collapsing by heating of the substrate surrounding the bore.

14. A system as claimed in any one of Claims 6 to 13 in which a flexible sealant is provided between the optical fibre and the substrate surrounding the bore at the free exit of the bore.

15. A system as claimed in any one of Claim 6 to 14 wherein the securing is limited to the section of the optical fibre within the substrate or tube or ferrule nearest to the end of the fibre.

16. A system as claimed in any one of Claim 6 to 15 in which the diaphragm is bonded to the end face of the tube or to the transparent plate mounted thereon by anodic bonding or diffusion bonding.

17. A system as claimed in any one of Claims 6 to 16 in which the reflectivity of one or both of the interfaces defining the cavity is increased by the provision of a reflective coating thereon.

18. A system as claimed in any preceding Claim in which the substrate comprising the processing interferometer is silicon or silicon-on-insulator or silica-on-silicon.

19. A system as claimed in any preceding Claim in which the processing interferometer is a Mach-Zehnder or Michelson interferometer.

20. A system as claimed in any preceding Claim in which the broadband light source(s) is integrated on the substrate comprising the processing interferometer.

21. A system as claimed in any preceding Claim in which a light detector is integrated on the substrate comprising the processing interferometer.

22. A system as claimed in any preceding Claim in which the broadband light source is a superluminescent diode.

23. A system as claimed in any preceding Claim in which the coherence length l_c of the broadband light source is in the range 35-55 μm.

24. A system as claimed in any preceding Claim in which OPD_s is in the range 100-160μm.

25. A system as claimed in any preceding Claim in which the difference between OPD_s and OPD_p is 5μm or less.

26. A sensing system substantially as hereinbefore described with reference to the accompanying drawings.

27. A sensing system as claimed in any preceding Claim arranged to sense pressure within an internal combustion engine.

28. A method of manufacturing an optical cavity for use as the sensing interferometer in an optical sensing system as claimed in any preceding Claim, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; securing an end of an optical fibre within a bore in a tube, ferrule or further substrate; optically polishing an end face of the optical fibre and of the tube and bonding the diaphragm to the said end face of the tube by anodic bonding or diffusion

bonding so an optical cavity is formed between the diaphragm and the said end face of the optical fibre, and the length of the optical cavity is substantially determined by the depth of the recess.

29. A method of manufacturing an optical cavity for use as the sensing interferometer in a sensing system as claimed in any of Claims 1 - 27, the method comprising the steps of: micromachining or etching a recess in a first substrate to form a diaphragm; bonding the diaphragm to one face of a transparent plate by anodic or diffusion bonding so as to define an optical cavity therebetween the length of which is substantially determined by the depth of the recess; bonding the opposite surface of the transparent plate to an end face of a tube, ferrule or further substrate; and securing an end of an optical fibre within the tube or ferrule or further substrate.

STATEMENT UNDER ARTICLE 19

The claimed invention relates to a sensing system using a particular type of sensing interferometer and a particular type of processing interferometer in combination. The sensing interferometer comprises a diaphragm with a recess which is etched or micromachined to define OPDs and the processing interferometer is integrated on a second substrate. It is only by using this combination of features that the system is able to make use of the advantages provided by a white-light measurement system. WO94/11708 does not teach the use of the specific type of sensing interferometer used in the present invention nor does it teach how the processing interferometer can be manufactured to enable OPDs and OPDp to be matched to the accuracy necessary to enable the advantages of using a white-light system to be realised. Other prior art discloses sensing heads which have some similarity to that used in the present invention but there is no teaching in the prior art that that the use of such heads in a white-light system will lead to the significant advantages provided by the invention. Thus, it is the combination of features of the sensing interferometer and features of the processing interferometer that enables these advantages to be realised. The prior art does not teach towards this combination of the benefits of this combination.

One of the applications of the invention is in the sensing of pressure within the cylinders of an internal combustion engine with the sensor head connected to the processing system by an optical fibre. The invention has enabled such a system to work successfully. Prior art systems have suffered from the disadvantage that it was difficult to distinguish between variations in the signal sensed due to pressure changes in the cylinder and those due to environmental factors, e.g. noise due to movement of the fibre linking the sensor head to the processing system.

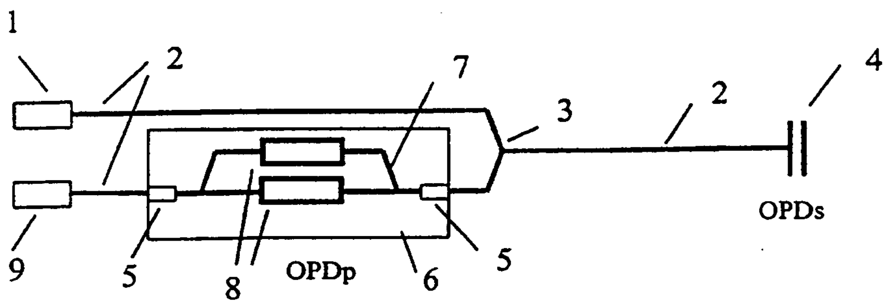

Fig.1

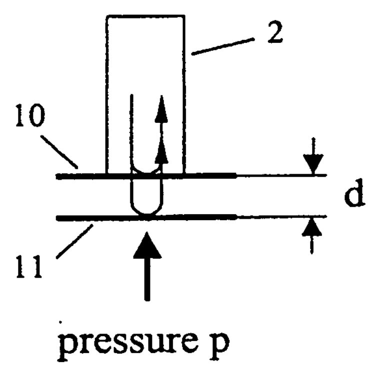

Fig.2

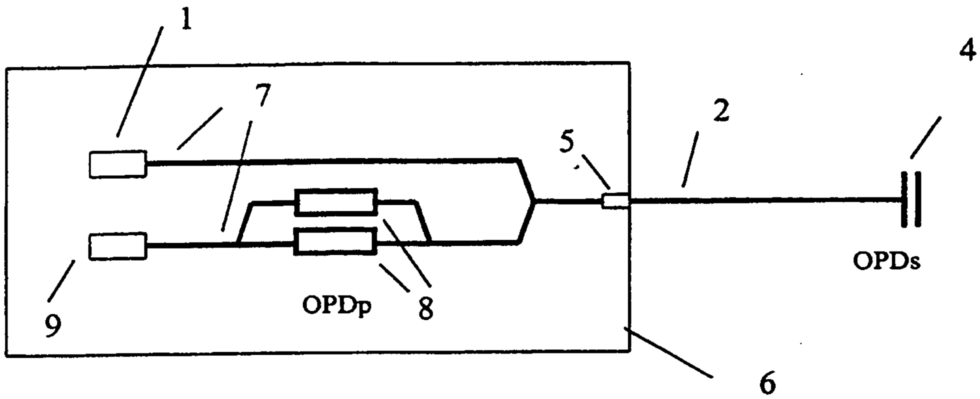

Fig.3

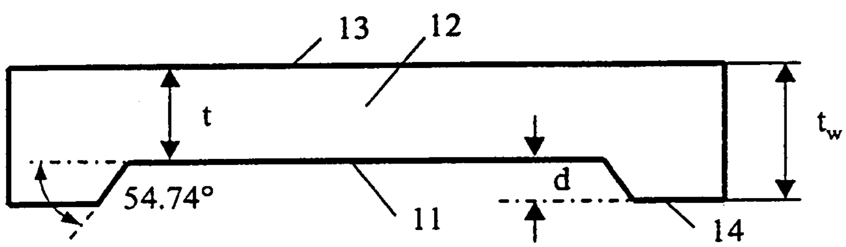

Fig.4a

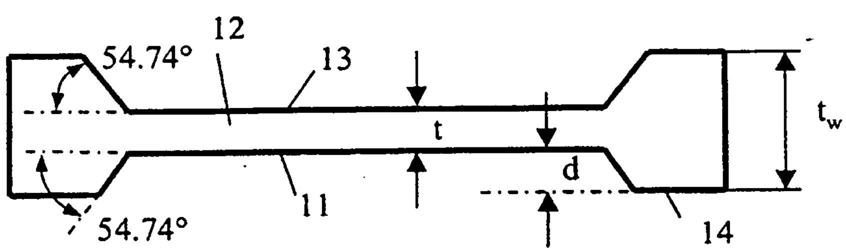

Fig.4b

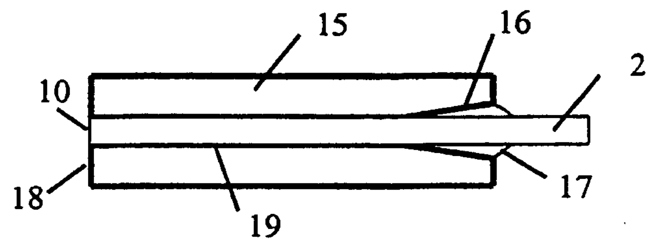

Fig.5

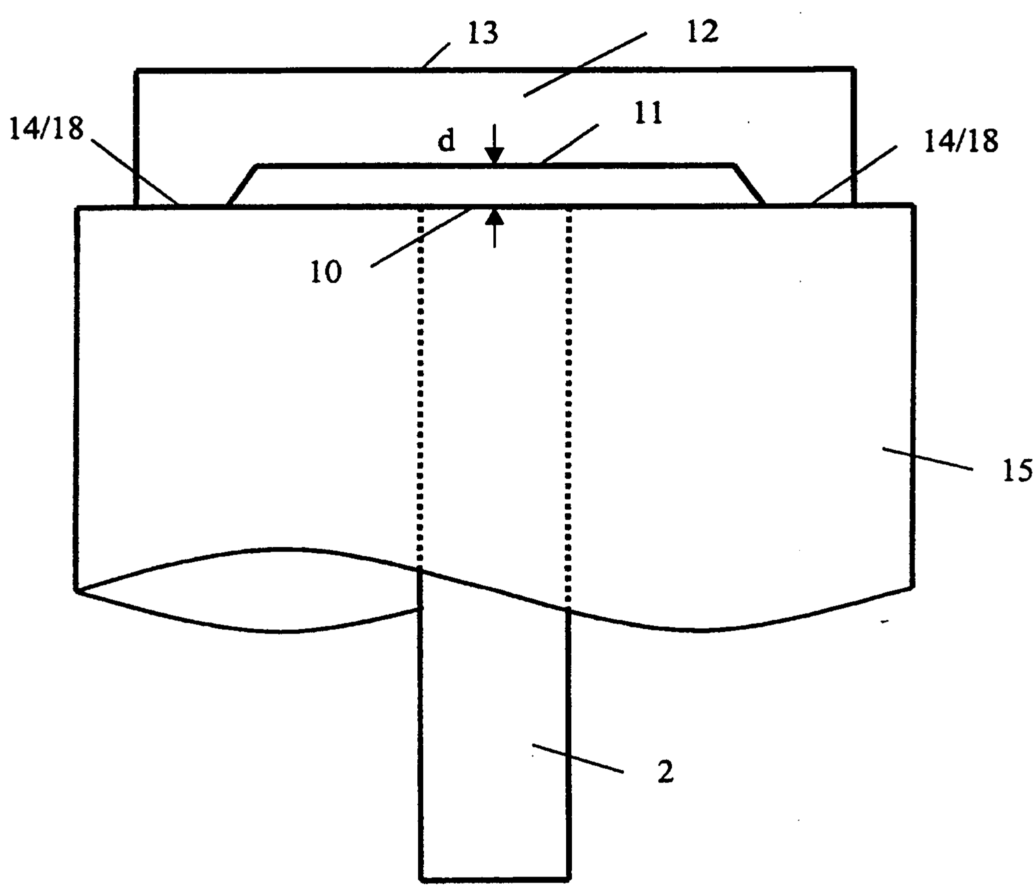

Fig.6

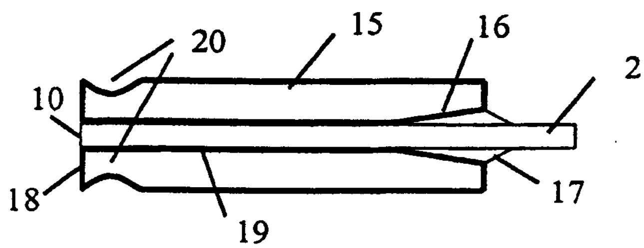

Fig.7

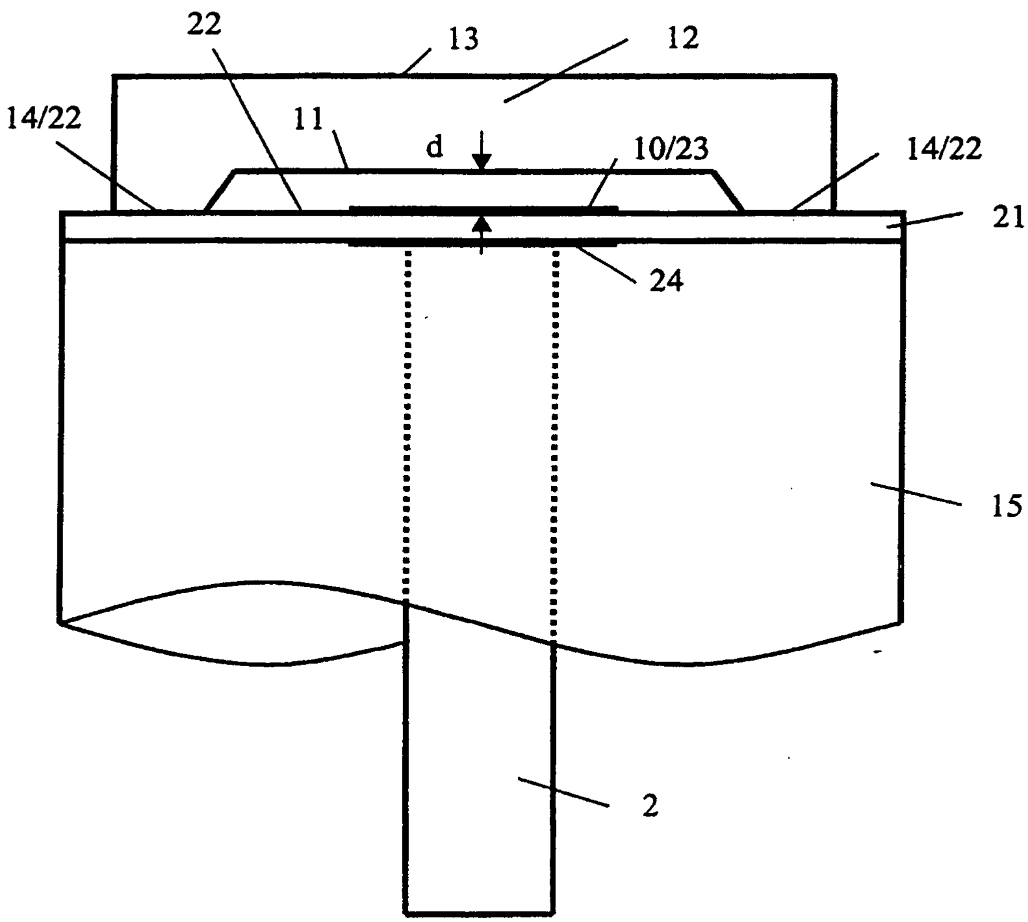

Fig.8

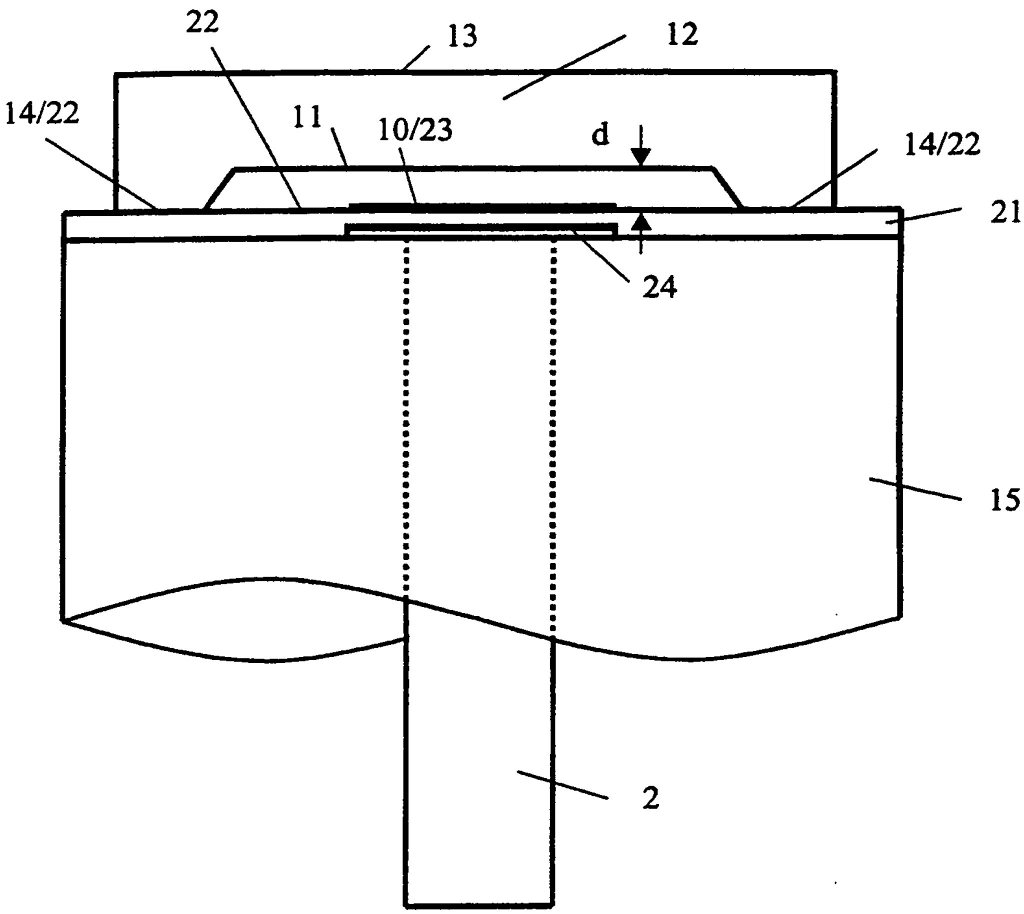

Fig.9